Wave Boundary Layer Processes Over an Irregular Bottom

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LONG-TERM GOALS

The broad long-term goal of this research is to extend understanding of wave and current processes over a very rough boundary, specifically that presented by a coral reef. From this understanding we aim to develop models that account for the effects of roughness on wave dissipation, sediment transport and biophysical interactions.

OBJECTIVES

The objective of this project is to relate measurements of roughness over a highly irregular bottom to observations of the wave flow at various scales, with the goal of developing a relation between roughness and wave and current energy dissipation and shear stress. The specific objectives include three elements: 1) observations of the small-scale turbulent processes over a wave orbital excursion; 2) a broad scale characterization of the wave field and its response to roughness; 3) high-resolution spatial surveys of the roughness over the study region. These observations will be further extended using a numerical model of the wave field in the nearshore region. Concurrent observations of sediment load and optical properties will explore the connection between shear stress and sediment suspension and transport over the complex reef topology.

APPROACH

A series of field observations have been carried out to address the objectives outlined above. Measurements of the wave and current field over a broad region of a coral reef are used to determine energy dissipation in an integral sense. Near-bed observations at smaller scales using acoustic profilers deployed on the Rough Boundary Profiler (RBP) then characterize the spatial structure of the boundary flow over a wave orbital excursion. The RBP moves an instrument package along a horizontal track over a distance of up to 3 meters (see figure 1), collecting data over a set time period at each location (typically 0.5 – 2 hours) thus allowing a spatial view of the near-bed flow. The 3 m track can be oriented in the swell direction within a window of +/- 10 degrees.

In parallel to the wave dissipation and boundary layer observations we have also completed high-resolution roughness surveys over the observational domain. Boat-based surveys examine the roughness at scales down to around half a meter and diver-based surveys determine variability at

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higher wavenumbers. The resulting roughness maps are intended to provide important information on small scales of reef roughness necessary for nearshore wave modeling.

Analysis of boundary layer data is being carried out by the PI along with PhD student Marion Bandet Chavanne. Details of the wave boundary layer dynamics and its effects on current boundary layers are the focus of Chavanne's PhD thesis, with completion expected in 2007. Vasco Nunes completed an MS thesis focusing on roughness field measurements and analysis with partial support from this grant. UH marine research engineer Kimball Millikan has been managing field operations and RBP design and operation. Observations carried out in collaboration with Stephen Monismith and Derek Fong (Stanford) are forming the foundation for the broad scale current and wave friction measurements. Field work carried out in collaboration with Tim Stanton (NPS) using the RBP has provided significant insight on small-scale near-bed processes.

WORK COMPLETED

In years one and two, work focused on development of the field observational array, RBP development and on general field operations. Efforts in year three centered on data analysis with limited focused field deployments augmenting continuous real-time data collection at Kilo Nalu.

Boat and diver-based surveys of roughness over the study area (see figure 2) were completed in the past year, with the results forming the basis for an MS thesis in Ocean Engineering (Nunes, 2005) and a journal publication (Nunes and Pawlak, 2006). Boat-based measurements used a pencil beam altimeter to measure high wavenumber variability in bed morphology. Resolution was limited to wavelengths of ~40 cm due to the acoustic footprint in deeper regions. Diver based measurements used a 'roughness bar' (McCormick, 1994) to extend the measurements to finer scales and to corroborate boat-based surveys. Sidescan imagery obtained from REMUS AUV-based observations (ONR Grant Number: N00014-04-1-0820) was used to compare roughness using a qualitative empirical scaling scheme. The roughness analysis is directed towards merging the various roughness parameters with wave field observations and numerical wave model output in order to establish a link between the physical roughness measurements and hydrodynamic wave friction at the study area. Wave modeling efforts using the COULWAVE Boussinesq model (Lynett et al, 2002), showed high variability suggesting that it may be difficult to extract the dissipation signal from the model results.

An array of wave gauges, current meters and current profilers was deployed on a reef on the south shore of Oahu (figure 2) for a two-week period in July, 2004 as part of a dye dispersal experiment carried out in collaboration with Stephen Monismith and Derek Fong (Stanford Univ.) (see Related Projects). Deployment of the instrument array, which aimed at characterizing the variations in currents and wave energy over a large area of the reef, coincided with two significant low frequency swell events. Current and wave field observations from the array are presently being analyzed to examine wave and current frictional characteristics. Analysis has thus far revealed very high friction levels (as expected), with spatial variability consistent with highly variable roughness. Observations of temperature fluctuations during the dye study using an offshore thermistor chain, along with instrument temperature records have revealed significant internal tide intrusion events in the nearshore zone. In addition to their role in driving nearshore currents, internal tide intrusions can alter benthic boundary layer geochemistry. Combined with wave driven fluxes across the seabed, this can significantly affect water column characteristics including optical and acoustic properties.

In August and September of 2004, the RBP was deployed at the study site with the goal of characterizing the boundary flow at smaller scales extending over the wave orbital amplitude. The August RBP deployment, carried out in collaboration with Tim Stanton (NPS), included use of a bi-static current Doppler velocimeter (BCDV) to obtain high resolution vertical profiles of the 3D near-bed velocities along the RBP axis, along with a scanned laser altimeter which mapped out the bed morphology. The September deployment used a downward-looking ADCP to obtain the phase-averaged flow field along the profiler axis. Each component of the velocity field is sampled separately along individual ADCP beams at each profiler position. The 2D flow field is then reconstructed as a function of wave phase using data from all instrument positions. RBP data analysis is continuing, with the goal of producing wave and current boundary layer frictional characteristics on the scale of a wave orbital amplitude. A third RBP deployment, in September 2005, coincided with the largest south shore swell in recent years. Significant wave heights neared 2.5 m with wave periods of 25 seconds. Analysis of ADCP and ADV data from the 2005 deployment has provided a highly resolved spatial and temporal view of the boundary layer structure and turbulence. Data analysis of RBP deployments at the south shore site is being completed, with the goal of establishing measurement accuracy and data quality in the spatial profiling and phase averaging methods. Results will be submitted for publication in late 2006.

In support of the RBP deployments, a powered fiber optic cable and offshore node was deployed allowing real-time data access and extended deployments. The cabled node has formed the foundation for the Kilo Nalu Observatory that provides access to the nearshore reef environment for ongoing and future experiments. The node provides ethernet and power via underwater connections for up to four subnode packages. A shore station provides direct access to the connections and remote access is available via wireless ethernet connection. An autonomous offshore wave gauge was also deployed at 20 m depth over the project duration to characterize the long-term wave climate at the observatory site. Wave, current and water property observations have been carried out nearly continuously since Oct. 2004, with real-time data and archived data products accessible at http://www.soest.hawaii.edu/OE/KiloNalu/.

RESULTS

Roughness was quantified from boat and diver-based surveys using spectral analysis. Spatial variations in spectral energy level within selected wavenumber bands were mapped to reveal variability in roughness for the complex reef morphology (see figure 3). Complete results have been outlined Nunes and Pawlak (accepted 2006). The measurements indicate that spectral energy can provided first-order quantification for reef and sand bed roughness. A characteristic spectral slope of 3 ± 0.7 was observed over the study domain extending throughout the spectral range considered. Variability in spectral energy at shorter wavelengths (<100 cm) was consistent with lower energy over sandy regions and higher energy over reef areas, as might be expected. Longer wavelengths (>100 cm) showed more homogenous spectral energy levels, suggesting that larger scales are related to underlying reef morphology that remains consistent independent of substrate type. The results were compared with roughness inferred qualitatively from REMUS sidescan imagery, with favorable results.

Detailed analysis of current and wave field data from the July 2004 dye dispersion experiment has been carried out, with details emerging on the broad scale features of the reef hydrodynamics. Figure 3 shows current data overlaid on the roughness data for the 63-100 cm wavenumber band. Logarithmic profiles were fitted to ADCP velocity profiles using least squares methods to yield measurements of

current bed stress over the two-week experiment. The analysis is complicated by the variation of the effective bottom location with current strength and direction, in addition to wave variability. Analysis of idealized profiles indicates, nonetheless, that while bed roughness values obtained from the least-squares analysis are questionable, measurements for bed shear stress (u_*) are robust. Given estimates for u_*, we can obtain a current friction factor (f_c) which, combined with local wave-induced velocities, can be used to obtain a crude estimate for wave friction factor (f_w) (c.f. Trembanis et al, 2004). Results of this analysis show significant scatter, although overall values are generally consistent with measurements by Lowe et al, 2005, carried out over a shallow reef flat. mil They used spectral methods to estimate the wave friction factor as a function of wave frequency, yielding values for f_w of 0.1-0.2 within the range of frequencies observed during our work. Figure 4 summarizes the results as a function of current direction, indicating average values for f_w of 0.04-0.07. These values are consistent within the error bars of either set of measurements. Bed roughness length scales can be inferred given estimates for f_w using commonly used parameterizations. This analysis yields mean roughness scales on the order of 30 cm, which is qualitatively consistent with diver based observations. Si ar analysis by Lowe et al, 2005 for the shallow reef flat case gave roughness scales of O(20 cm). Further analysis is necessary to define a quantitative connection with the spectral based roughness measurements.

We have also obtained estimates for f_c and f_w using near-bed observations from an array of three single-point acoustic velocimeters. A similar logfit analysis was used to obtain current shear stress. The analysis is more problematic here since only two or three velocity points are available for a fit, although results compare favorably with acoustic profiler data. Bed stress was also estimated using the inertial dissipation method which obtains friction velocities using measurements of turbulent kinetic energy within the current boundary layer (Huntley, 1988). While the various methods used all exhibited high scatter in the results, average values at all sites compared surprisingly well. The directional dependence of wave and current friction factors is illustrated in figures 4a and 4b. The aim is to correlate directional dependance with measured bed roughness as shown in figure 3. The data is suggestive of correlations in some cases, although the scatter is considerable. For example, we may expect directional variability associated with a large sand bed between sites P3 and AF, indicated by lower RMS values in figure 3. Indeed, the data for P3 tends to show higher friction associated with eastward flow coming off of the reef. No significant variation is seen in the data at AF, however. Further study is underway to draw definitive conclusions.

Figure 5 and 6 show results from RBP deployments from Fall 2004. Data from the August 2004 BCDV deployment (Figure 5) shows enhanced spectral energy around a coral head. The data is consistent with a spatially variable boundary layer with thicknesses between 20 and 30 cm. Figure 6 shows phase-averaged amplitude and phase data (6a, 6b respectively) with a snapshot of the phase-averaged velocity field shown in 6c. Data in the figure represents along-beam ADCP data collected over a 3-day swell period and averaged together by wave phase for wave events matching narrow period and amplitude criteria. The phase plot in figure 6b indicates the wave phase at which the local velocity vector is aligned with the semi-major ellipse axis and highlights the phase shift near the bed characteristic of the oscillating boundary layer flow. Velocity amplitude (figure 6a) shows spatially variable amplification outside the near bed region with a sharp decay in magnitude near the bed. The bottom is represented by contours of ADCP correlation magnitude which increases sharply at the bed.

The September 2005 RBP deployment, coincident with a significant swell event over 5 days, obtained profile data over the full 3 meter profiling range. Figure 7 includes an example of the RNP data,

showing the evolution of turbulent kinetic energy as a function of wave phase normalized by the local wave kinetic energy, highlighting the spatially variable production of turbulence at particular wave phases, associated with roughness elements along the rough reef surface. The turbulent kinetic energy is inferred from the variance of velocity relative to the phase averaged flow field. While a portion of this velocity variance is due to ping-to-ping measurement uncertainty, the spatial structure is indicative of areas of high turbulence. In addition, observations included near-bed measurements using an ADV to investigate strong near-bed rectified flows observed in the BCDV dataset. These types of mean flows are characteristic of near-bed flow over inhomogenous boundaries and provide a mechanism for enhanced momentum transfer (Pawlak and MacCready, 2003).

IMPACT/APPLICATIONS

We expect that our observations of the interactions between waves and currents and the rough boundary over a coral reef will lead to more accurate parameterizations of bed shear stress and wave and current dissipation as a function of roughness that can be applied in wave and sediment transport modeling over irregular boundaries. Nearshore numerical wave models typically use friction parameterizations based on uniform roughness, which is only loosely related to the actual roughness over a reef. These observations will be critical to accurate modeling efforts which are being carried out as part of new ONR funded work at Kilo Nalu (see Related Projects below). Illuminating the turbulent processes over a rough boundary will have further benefits to understanding oscillating flows over irregular boundaries in general with applications to flow around support structures, buried objects and pipelines and cables, as well as to larger scale oceanographic boundary flows.

A significant impact of the work underway has been the establishment of the cabled Kilo Nalu Nearshore Reef Observatory. This has enabled real-time access to data, facilitating deployment of instruments that would otherwise be limited to short-term deployments. The initial Kilo Nalu infrastructure, deployed largely with support of this ONR grant is presently being augmented under the support of an NSF Benthic Boundary Layer CoOP funded project in addition to further ONR funded research. The observatory expansion includes improved capabilities at 10 m along with new nodes 20 and 30 m nodes with the goal of illuminating benthic biogeochemistry and physics.

RELATED PROJECTS

We have been working closely with researchers from UH (Marlin Atkinson, Jim Falter) and Stanford University (Stephen Monismith, Jeff Koseff). Their studies, funded by NSF, aim to relate wave boundary layer processes to nutrient uptake by coral communities. They have constructed an oscillating flume to examine the chemical aspects of the flow and have carried out field observations exploring the dissipation of waves over a reef flat in Kaneohe Bay. We participated in observations in August, 2003 where the pilot version of the RBP was deployed. This data set has thus far yielded one publication (Lowe et al, 2005) with further data analysis underway.

In addition, we have carried out a dye dispersal study at the reef observatory site in July of 2004, in collaboration with Stephen Monismith and Derek Fong along with Stanford graduate researchers Ryan Lowe and Nicole Jones. This pilot experiment included deployment of a wave/current measurement array that will provide data for the wave boundary layer study (discussed above). The purpose of the dye study is to examine wave-current interactions over the rough reef boundary through its effect on dispersal mechanisms. The study further aimed to examine Lagrangian transport mechanisms in the

nearshore reef environment. Dye was released at approximately 10 m depth using an automated source, with varying current and wave forcing. The dye cloud was then tracked using a REMUS autonomous underwater vehicle equipped with a fluorometer.

The Kilo Nalu observatory is also being utilized by a number of other projects. A UH Sea Grant funded study to monitor nearshore water quality (PIs: G. Pawlak and E. H. De Carlo) includes deployment of real-time chemical sampling instrumentation along with tide, current and wave measurements. An NSF funded project to examine sediment porewater-seawater exchange (PIs: F. Sansone, M. Merrifield, G. Pawlak) will also make use of the observatory to carry out field observations. As described under "Impacts/Applications", a new NSF CoOP study (PI's: G. Pawlak, F. Sansone, M. McManus, E. DeCarlo, T. Stanton) will significantly expand the Kilo Nalu infrastructure. A new ONR funded project (award number N00014-06-1-0224, PI's: G. Pawlak, M. Merrifield) will also make use of the observatory to examine the effects of offshore internal tide forcing on nearshore currents and sediment transport. This work also includes expansion of the Kilo Nalu array to include additional offshore measurements of temperature and velocity profiles. The YIP work will provide important input to the new project on wave and current boundary layer dynamics for modeling efforts using DELFT3D.

This research program has already benefitted considerably from the acquisition of a REMUS AUV as part of an ONR DURIP (PIs: R. Wilkens, G. Pawlak, C. Fletcher). REMUS data has been used for validating roughness survey results and for characterizing bed morphologies at Kilo Nalu.

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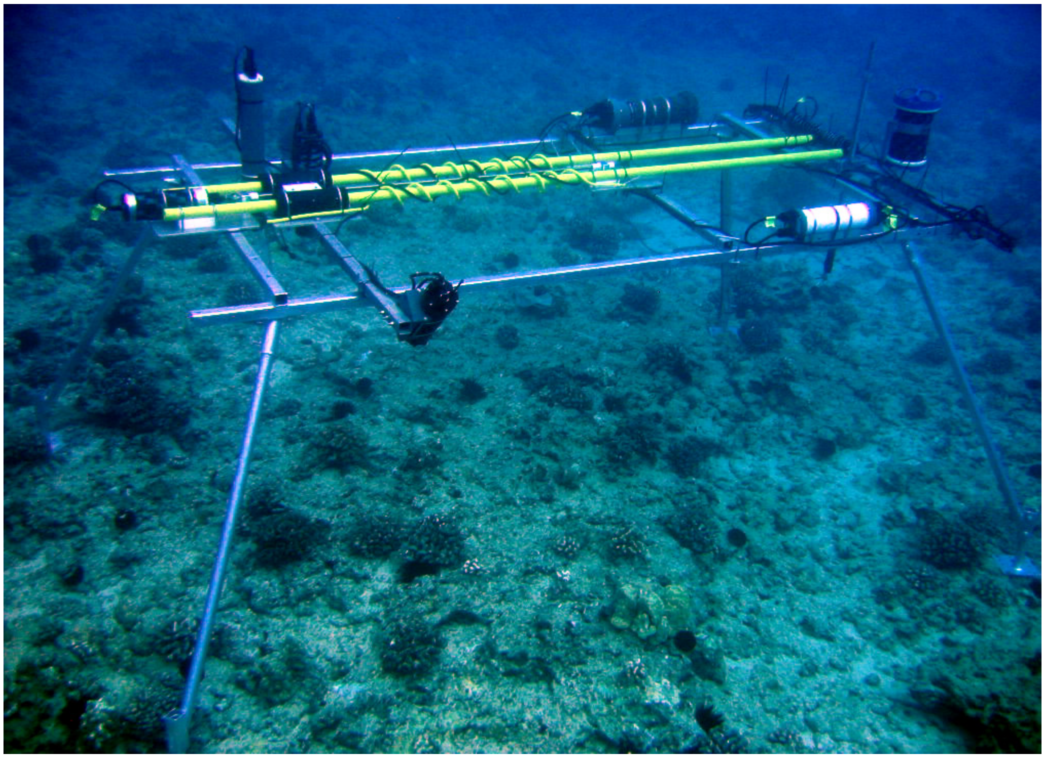

Figure 1: Rough Boundary Profiler (RBP). The automated profiler moves instrument packages along a 3 m track (yellow bars) allowing resolution of the near-bed spatial structure. A shore cable connection provides real-time data and power. The instrument array pictured includes BCDV and scanned laser altimetry system (Stanton, NPS) along with ADV and upward looking ADCP.

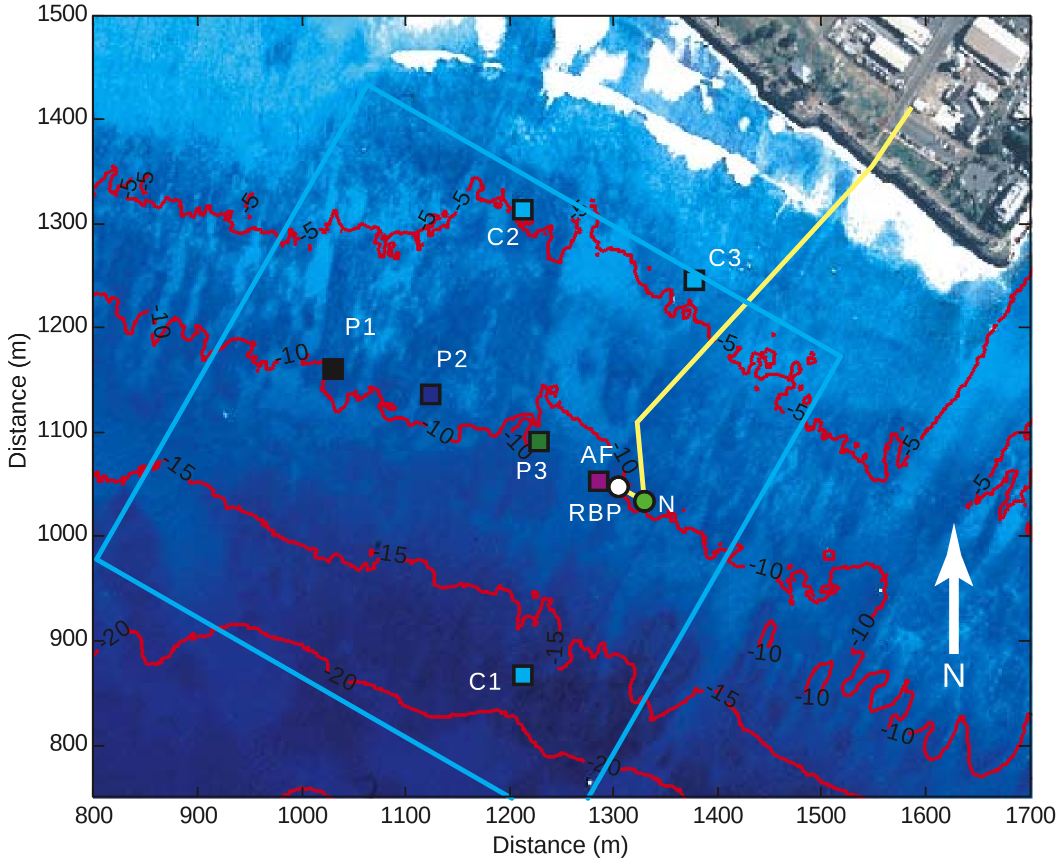

Figure 2: Field observational array, July/Aug. 2004. Aerial view of Kakaako Waterfront Park and offshore reef region with SHOALS bathymetry overlaid (contours at 5m intervals). Instrument array for dye dispersal experiment included 3 ADCPs (P1,P2, P3), 3 Aquadopp single point current meters (C1, C2, C3), and an instrument frame with 3 ADV current meters (AF). Kilo Nalu cabled observational array is shown , including the RBP profiling platform (RBP, white circle), central node (N, green circle) and shore cable (yellow).

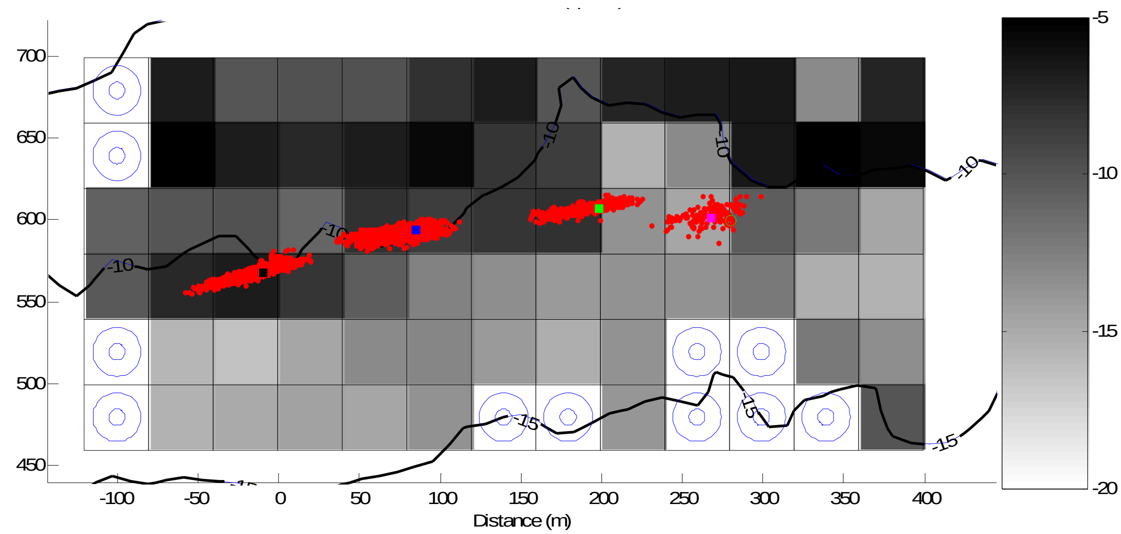

Figure 3: Spectral roughness energy (expressed as RMS height in cm) for the 63-100 cm band from boat-based altimetry surveys. Boxes with insufficient data are shown with targets. Current scatter data from July 2004 experiment are overlaid. Sites AF, C1, C2 and C3 (see figure 2) show greater scatter since these are near-bed velocities. Bathymetry contours at 5m intervals are also shown.

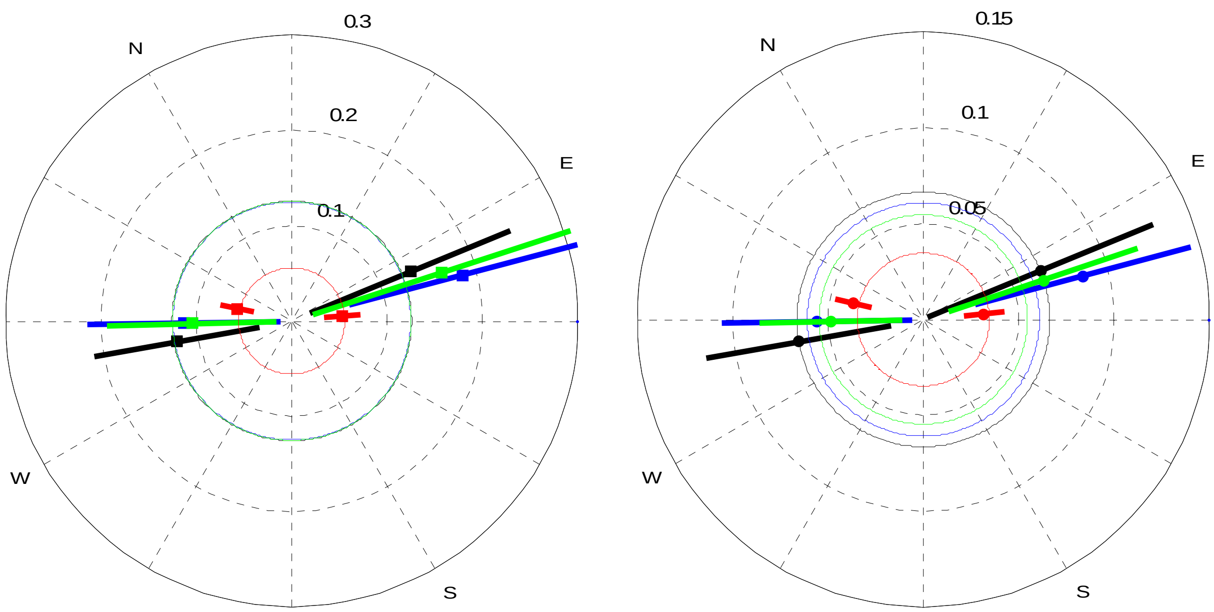

Figure 4: Current (left) and wave (right) friction factors as a function of current direction. Colors indicate measurement site (as shown in figure 2). Direction represents direction of mean east- or westward currents. Symbols indicate average value for given direction with lines representing standard deviation in measurements. Colored circles indicate overall average for each site. Note that the axes are rotated by 30 degrees to compare with figure 3.

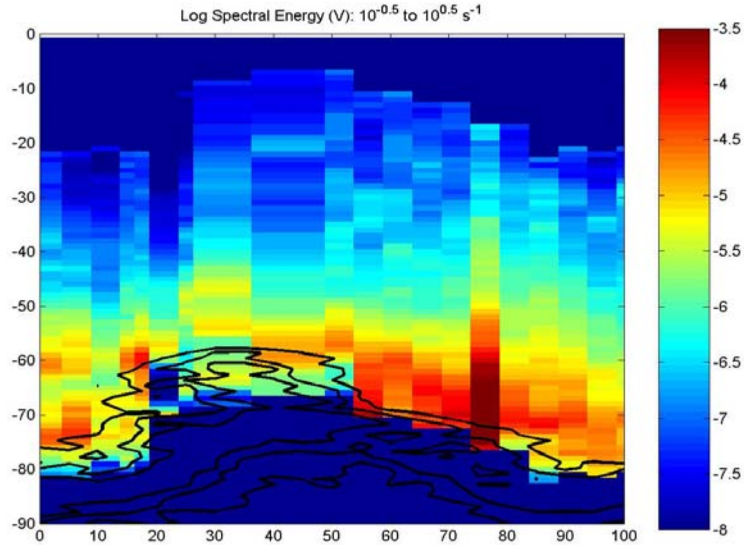

Figure 5: Near-bed flow variability as inferred from 8/04 BCDV. BCDV-derived spectral energy is indicative of near-bed turbulence surrounding a coral head. Contours here indicate acoustic backscatter levels. Vertical axis is relative to instrument location. The horizontal axis indicates cross-shore position.

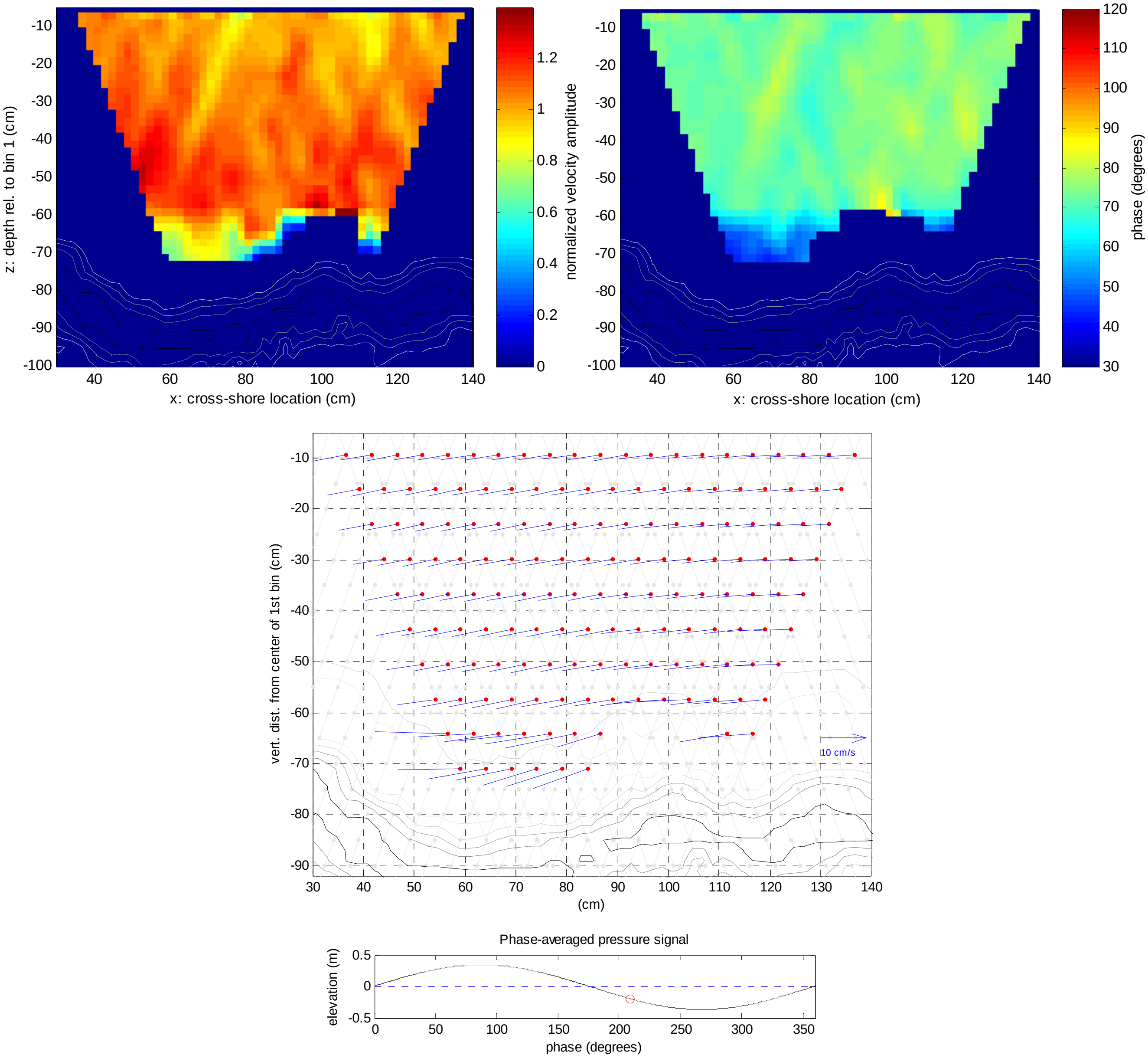

Figure 6: Phase averaged velocity field data from September, 2004 RBP deployment. a) Phase averaged velocity amplitude, normalized by linear wave velocity. Contours indicate ADCP correlation magnitude highlighting the bottom location. b) Phase angle for semimajor ellipse highlighting phase lead near the bed. c) Phase averaged velocity field for zero downcrossing again highlighting phase lead along with flow turning in near-bed flow.

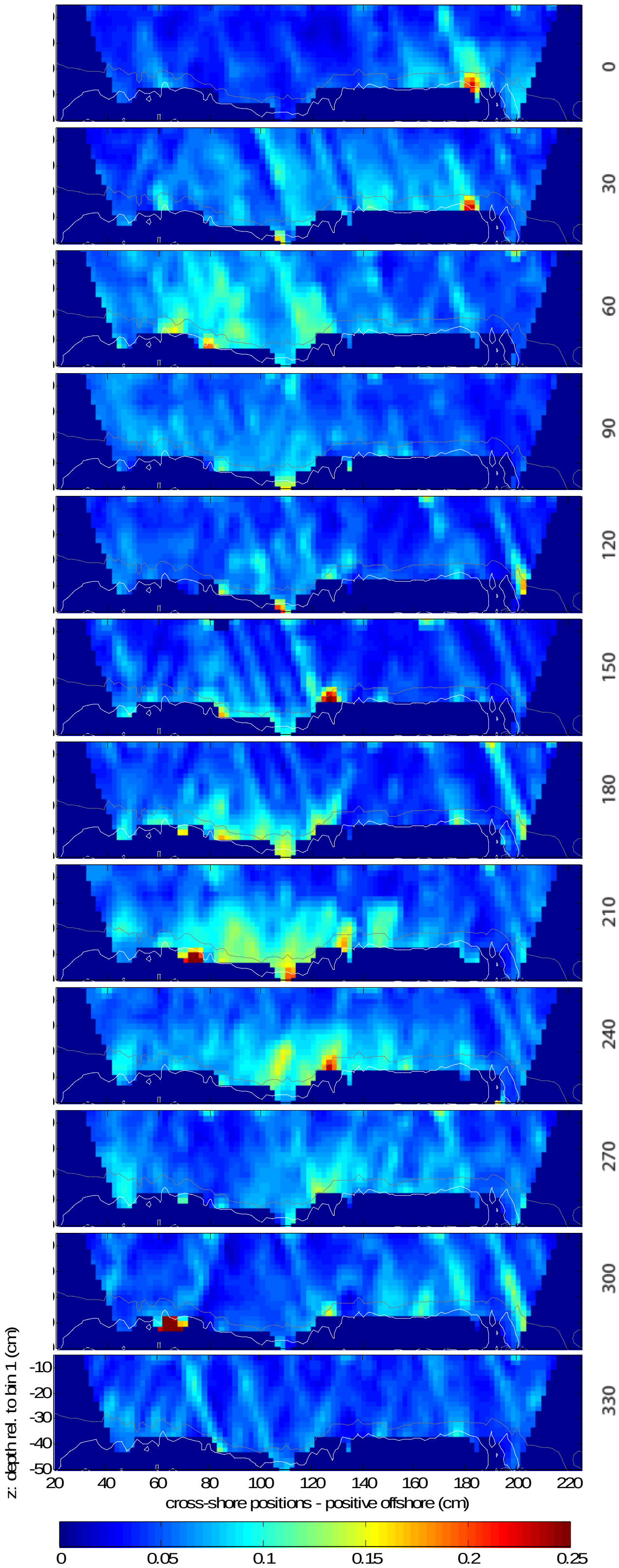

Figure 7: Phase-averaged turbulent kinetic energy (normalized) from RBP. Wave phase is indicated along the right, relative to zero upcrossing. High production is observed at 60 and 210 degrees.